

Super-Giant Glitches and Quark Stars: Sources of Gamma Ray Bursts?

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Abstract

When a spinning-down neutron star undergoes a phase transition that produces quark matter in its core, a Super-Giant Glitch of the order $\Delta\Omega/\Omega \sim 0.3$ occurs on time scales from 0.05 seconds to a few minutes. The energy released is about 10^{52} ergs and can account for Gamma Ray Bursts at cosmological distances. The estimated burst frequency, 10^{-6} per year per galaxy, is in very good agreement with observations. We also discuss the possibility of distinguishing these events from neutron star mergers by observing the different temporal behavior of gravitational waves.

Subject headings: dense matter—elementary particles—gamma rays:bursts—stars:neutron

1. Introduction

Although numerous explanations of Gamma Ray Bursts (GRBs) have been proposed, the exact nature of the GRB source, e.g., a neutron star binary merger (Paczynski 1986), a halo neutron star quake (Blaes, Blandford, & Madau 1990), or a “failed” supernova (Woosley 1993), remains hidden behind a relativistically expanding fireball. Most observational consequences result from radiation processes (see Mészáros & Rees 1993 and Thompson 1994 for “generic” models for GRBs) and are independent of the birth details. Hence, when considering the possible sources of GRBs, the essential parameters are the time scale, the initial energy, the volume of the source, and most importantly, the birth rate of GRBs, which is about 10^{-6} per year per galaxy as indicated by observations (Piran 1992).

Here we outline how a neutron star might change into a hybrid star, which has a quark core and a neutron star crust (e.g., Rosenhauer et al. 1992). That is, a spinning-down neutron star increases in central density towards the critical density ($\rho_{\text{cr}} \sim 3\rho_0$, where $\rho_0 \simeq 2.8 \times 10^{14}$ g cm $^{-3}$ is the nuclear density) for phase transition from neutron matter to quark matter (see Rosenhauer et al. 1992 and references therein).

Various Equations of State (EOSs) predict different central densities for a $1.4M_{\odot}$ neutron stars, and some neutron stars may have central densities very close to ρ_{cr} . They can evolve from the initial situation with central density below the critical density to ρ_{cr} during the spin-down process. A phase transition occurring inside the star causes it to collapse, thus releasing gravitational energy in the form of a GRB. A sudden spin-up, much more dramatic than any pulsar glitches observed, then takes place, which we call “Super-Giant Glitch (SGG)”.

2. Phase Transition and Super-Giant Glitch

Baym and Chin (1976) studied the structure of a hybrid star, but they considered quark matter made of u and d quarks, which is stable only at densities higher than $10\rho_0$ and is unlikely to be reached in the center of neutron stars. Later, people found that the strange quark matter (made of approximately equal numbers of u , d and s quarks) has significantly lower energy than u , d quark matter at the same pressure (Farhi & Jaffe 1984; Witten 1984). Witten even considered the possibility that strange quark matter is more stable than ^{56}Fe and is the absolute ground state of nature.

With the conjecture that strange quark matter is stable at zero pressure, some authors have studied the structure of strange stars (Alcock, Farhi & Olinto 1986a) and have even proposed a novel model which states that the GRB of 5 March 1979 was formed when a small lump of strange matter struck a rotating strange star (Alcock et al. 1986b). It was also proposed (Olesen & Madsen 1991) that a neutron star may burn into a strange star on time scales from 0.05 seconds to a few minutes. The time scales depend mainly on the time scale for the weak interaction and a diffusion coefficient (see Olesen & Madsen 1991 for details), and does not rely on assuming whether strange quark matter is absolutely stable or not.

However, the existence of pulsar glitches (Alpar 1987) seems to be strong evidence against the existence of strange stars at all and, hence, the mechanism of GRBs from strange stars (Kluźniak 1994). Whether or not strange quark matter can be absolutely stable depends on parameters like the bag constant in the quark model and is unclear today, although it is believed that strange quark matter is more stable than u , d quark matter and may be

formed via deconfinement phase transition at a critical density of about $3\rho_0$.

Here we consider the case that strange quark matter is stable only at high pressure with a critical density $\rho_{\text{cr}} = 3.0\rho_0$ for the phase transition. The mechanism of the conversion from a neutron star to a hybrid star is that a small amount of quark matter is formed in the center once the central density of the neutron star reaches the critical density, and since the EOS of the quark matter is much softer than that of the neutron matter due to the asymptotic freedom property of quark-quark interactions, the newly formed quark matter cannot sustain the high pressure in the stellar center and will be more highly compressed. As a result, the whole star collapses until another stable configuration, a hybrid star, is reached.

This point can also be seen from the mass-central density plot of hybrid stars (Rosenhauer et al. 1992), where a discontinuous part in the curve indicates that a hybrid star cannot have a quark core of arbitrary size. A $1.4M_\odot$ hybrid star is stable only when it has a central density of about $10\rho_0$ and has more than half of its mass in the quark phase. Hence, once the central density of a neutron star reaches ρ_{cr} , there must be a sudden collapse. Inside a hybrid star, the quark matter exists under high pressure, whereas in Witten's hypothesis (Witten 1984) the strange matter is the absolute ground state and is stable at zero pressure. The mechanism of burning a neutron star to a strange star would be that a small lump of strange quark matter "eats up" all the neutron matter.

There are numerous EOSs for the neutron matter. We use that of Bethe & Johnson (1974). It has very similar behavior to the phenomenological EOS of Sierk and Nix (1980) used in the detailed study of the structure of a static hybrid star by Rosenhauer et al (1992). A $1.4M_\odot$ neutron star with Bethe & Johnson's EOS has a radius of about 12 km (Shapiro & Teukolsky 1983), while a hybrid star of the same mass has a radius of less than 10 km (Rosenhauer et al. 1992).

The gravitational energy released in an SGG can be estimated by

$$E \sim \frac{GM^2}{R} \left(\frac{\Delta R}{R} \right) \simeq 10^{53} \left(\frac{\Delta R}{R} \right) \text{ ergs}, \quad (1)$$

and is about 10^{52} ergs in our case. Most of the dissipated energy is probably released in the form of neutrinos. If a small part of the total energy goes into γ rays, it will be large enough to account for the

GRBs at cosmological distances and to explain their isotropic distribution (Palmer 1993). Also, the phase transition and collapse can occur only once in a neutron star's life. This explains the lack of recurrence of GRBs.

To estimate the spin-up rate of the star, we use the approximation of moment of inertia proposed by Ravenhall and Pethick (1994),

$$I \simeq 0.21MR^2\lambda(R) = 0.21\frac{MR^2}{1 - 2GM/Rc^2}, \quad (2)$$

which is in fact a general relativistic correction to that of an incompressible fluid in the Newtonian limit $I = 0.4MR^2$. Equation (2) is accurate to 10% for EOSs without phase transitions, and to about 30% for those EOSs predicting phase transitions. This is good enough in our order of magnitude estimate.

The moment of inertia of the neutron star, according to equation (2), is $I_{\text{neutron}} \simeq 1.3 \times 10^{45} \text{ g cm}^2$. The moment of inertia of the hybrid star is $I_{\text{hybrid}} \simeq 1.0 \times 10^{45} \text{ g cm}^2$. The change of angular velocity is then $\Delta\Omega/\Omega \sim 0.3$ and is 10^6 times larger than the largest pulsar glitches observed. The time scale for the SGG is similar to that for burning a neutron star into a strange star calculated by Olesen & Madsen (1991), and is from 0.05 seconds to a few minutes. A more realistic description is complicated by the high temperature during the SGG, while EOSs for finite temperature are very unclear. Also, the super-Eddington radiation may blow away the surface of the star.

3. Burst Frequency

In the spin-down process, the central density of a neutron star increases. The detailed study of Cook, Shapiro, & Teukolsky (1994) shows that the change of the central density ($\Delta\rho_c$) is about 2.4% for a $1.4M_\odot$ neutron star spinning-down from an initial period of 4.3 ms to a static state. We need to extrapolate from this to neutron stars with different spins. We note that the small deviations of pressure and density from their equilibrium values have a rough relation of $dp/p \sim d\rho/\rho$ for a polytropic EOS, and that the centrifugal force $\propto 1/P^2$, hence $d\rho/\rho \propto 1/P^2$.

We have very little knowledge about how fast a newborn neutron star rotates, either theoretically or observationally. The only piece of information available is that the Crab pulsar was born with a rotational period of about 20 ms (Manchester & Taylor

1977), so it will have a central density increase of about $\Delta\rho_c/\rho_c \simeq 0.001$ in its lifetime.

Assuming a phase transition critical density ρ_{cr} , only those neutron stars born with central densities $\rho_{\text{cr}}(1 - \Delta\rho_c/\rho_c) < \rho_c < \rho_{\text{cr}}$ would have the chance to undergo the SGGs. For example, in the case of $\rho_{\text{cr}} = 3.0\rho_0$, and assuming all neutron stars were born at the same initial period (P_i) of 20 milliseconds, the density range is $2.997\rho_0 < \rho_c < 3.0\rho_0$. Neutron stars with lower central densities cannot reach the critical density in their whole lives. Those with higher central densities should be born as hybrid stars.

Radio observations of binary pulsar systems together with statistics of neutron star mass distributions have given a strong constraint on neutron star masses, which lie in a narrow range from $1.0M_\odot$ to $1.6M_\odot$ (Finn 1994). For the EOS of Bethe & Johnson (1974), the central densities of these neutron stars range from a lower limit $\rho_l \simeq 2.5\rho_0$ to an upper limit $\rho_u \simeq 4.3\rho_0$ (Shapiro & Teukolsky 1983). It is apparent that we need EOSs predicting $\rho_l < \rho_{\text{cr}} < \rho_u$ to make the sudden phase transition possible.

We assume the neutron star central densities are evenly distributed in this range. The birth rate of GRB events in units of per year per galaxy (R_{GRB}) in our model will be the probability for a neutron star to undergo an SGG times the birth rate of neutron stars (R_{NS}),

$$R_{\text{GRB}} = \frac{\rho_{\text{cr}}(\Delta\rho_c/\rho_c)}{\rho_u - \rho_l} R_{\text{NS}} \simeq 10^{-6} \left(\frac{P_i}{20 \text{ ms}} \right)^{-2} \left(\frac{R_{\text{NS}}}{10^{-3}} \right), \quad (3)$$

where R_{NS} is an average over all types of galaxies, in units of per year per galaxy. R_{GRB} does not strongly depend on the exact critical density since $\rho_{\text{cr}}/(\rho_u - \rho_l)$ most likely has an order of unity. With typical values of initial period and average neutron star birth rate the result from equation (3) is in very good agreement with observations.

There are many factors affecting this estimate. First, some stars may be born as hybrid rather than neutron stars even with much lower central densities, because the high temperatures of newborn neutron stars favor the quark-hadron phase transition. Second, the stars may be born at rotational periods longer or shorter than 20 milliseconds. The uncertainties of the EOSs should also be kept in mind. There are numerous published EOSs for high-density matter, while we only know that for a given density with a definite composition, there should be a correct

one. A stiff mean field EOS (e.g., Baym & Pethic 1979) predicts a $1.4 M_\odot$ neutron star with $\rho_c \simeq 1.4\rho_0$, which does not undergo an SGG even for the largest possible ρ_c increase (30% according to Cook et al. 1994); while a soft EOS like that of Reid (e.g., Baym & Pethic 1979) gives $\rho_c \simeq 10\rho_0$ and predicts that the star should be born as a hybrid star. If either of these EOSs is correct, there will be no SGGs at all. From equation (3), we can also give an upper limit for the SGG birth rate for the EOSs that favor the phase transition (like that of Bethe & Johnson). With limiting values, $P_i \sim 0.5 \text{ ms}$ and $R_{\text{NS}} \sim 0.02$ per year per galaxy, R_{GRB} can be as large as 10^{-2} .

4. Discussions

The predicted rate from the neutron star merger models is also close to observations (Piran 1992), but these models have difficulties like the inevitable disruption of the stars and the rapid quenching of the γ ray emission due to the cooling and expansion of the ejected baryonic matter. In our model, there is less possibility of disruption. Hence, the problems of rapid quenching and contamination are minimized. On the other hand, the SGGs offer much more energy than ordinary starquake models (Blaes et al. 1990). In the latter models, the GRBs are interpreted as events within our own Galaxy and have apparent difficulties in explaining the observed isotropic distribution. The SGG model proposed here is rather natural, since most pulsars are spinning-down and increasing their central densities. We do not have to assume stable strange matter or other exotic and rare events. The phase transitions inside neutron stars are not solely quark-hadron phase transitions. Other phase transitions like pion condensation may also result in SGGs and account for GRBs.

If an SGG happens late in the spin-down history of a neutron star, it is a nearly spherical collapse and produces no gravitational radiation. Most of the observed millisecond pulsars are believed to be old and have been spun up by accretion. They have weak magnetic fields and low spin-down rates which do not favor SGGs. However, it is possible that some neutron stars may be born at high initial spins (Michel 1987; Lai & Shapiro 1995). If an SGG happens in a neutron star with rotational period about 1 millisecond, it may produce detectable quadrupole gravitational radiation. The collapse with rotation is similar to the lowest quadrupole mode of vibration of a rotating

neutron star for which the power of gravitational radiation has been estimated for a vibration amplitude of $0.1R$ (which is approximately equal to the stellar surface displacement in our SGG model) and a rotational period of 1 millisecond (Wheeler 1966; Misner, Thorne, & Wheeler 1973). The power is about 10^{50} ergs sec^{-1} and is comparable to that in a neutron star merger (Kochanek & Piran 1993; Centrella & McMillan 1993; Lipunov et al. 1995), but is apparently associated with different waveforms. So it is possible to discriminate the SGGs from neutron star mergers with gravitational wave detectors like the Laser Interferometer Gravitational Wave Observatory (LIGO; see Abramovici et al. 1992).

In conclusion, we propose that the sudden transformations from neutron stars to hybrid stars may account for the Gamma Ray Bursts at cosmological distances. We also give explanations to the properties of GRBs: the duration of bursts, burst frequency, the lack of recurrence and the isotropic distribution. If this model is eventually confirmed in further observations, in addition to improving our understanding of GRBs, the existence of quark matter can be proved. Otherwise, the EOSs and the parameters related to the phase transition in this *Letter* will be challenged, although they have been widely studied in literature. In this way, we may be able to give constraints on some EOSs and/or parameters like the bag constant in the quark model, which is essential in determining the critical density for the quark-hadron phase transition.

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